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Self-paced work in sleep deprived subjects

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The effect of sleep deprivation and physical fatigue on self-paced work was determined in two experiments simulating sustained combat engineer operations. In experiment A, four subjects went without sleep for 69 hours. During this period they performed only four physically demanding tasks, three of them in the last 24 hours. Continuous recordings of heart rate (HR) indicated that sleep deprivation, in the absence of physical fatigue, had no effect on work intensity and the period of fatiguing work (HR above 120 beats min^{-1}). In experiment B, six subjects carried out a full schedule of physically demanding tasks during a period of sleep deprivation lasting 47 hours. Some of the tasks were repeated at least once so that the effects of sleep loss and physical fatigue could be assessed. For the first 14 hours of experiment B, the subjects worked at an average HR of 120 beats min^{-1}, equivalent to an energy expenditure of 35–40% of maximal oxygen uptake in fit young men. In the remainder of the sustained operation, work intensity declined and the subjects worked at HRs above 120 beats min^{-1} for shorter periods. Rating scales confirmed that these changes coincided with the development of physical fatigue. Since sleep deprivation was without effect in experiment A, the decline in self-paced work intensity in experiment B was attributed to the combination of physical fatigue and sleep deprivation.

1. Introduction

In the industrial or military workplace, the work tends to be intermittent and the worker sets his own pace (Astrand 1967, Gertner *et al.* 1984, Harber *et al.* 1984, Rodahl *et al.* 1974, Smith *et al.* 1985). In spite of this, average energy expenditure appears to be remarkably consistent when expressed relative to maximal oxygen uptake ($\dot{V}O_2$max). In those civilian occupations which still require significant manual labour, the upper limit for an eight hour working day is considered to be 35–40% of $\dot{V}O_2$max determined by a treadmill protocol (Astrand and Rodahl 1977, Michael *et al.* 1961, Simonson 1971). Investigations by Astrand (1967) for the building trade, by Spurr *et al.* (1977) for sugar-cane loaders, by Nag *et al.* (1978) for Sherpa porters, and by Rodahl *et al.* (1974) for coastal fishermen all confirm that the average energy expenditure for an eight hour day did not exceed 35–40% of $\dot{V}O_2$max.

The military is one of the few organizations interested in a work period which extends beyond the normal eight hours. On the assumption that future battles will continue day and night, it must be concerned with the effect of sleep deprivation on military performance. In sustained operations involving infantry and other ground forces, the effect of sleep loss is often compounded by physical fatigue. This paper describes two military manoeuvres, both simulating sustained combat engineer operations. In the first (experiment A), the subjects were sleep deprived for 69 hours, but were not physically fatigued; in the second (experiment B), they were assigned a

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full schedule of work throughout a 47-hour period without sleep. Heart rate (HR), recorded continuously and unobtrusively, was used to assess work intensity and the time devoted to fatiguing work (*HRs* above 120 beats min^{-1}) in both experiments. The objective was to assess the separate effect of sleep deprivation on self-paced work.

2. Materials and methods

2.1. *Subjects*

There were four subjects in experiment A and six in experiment B. All were males, aged 18–26 years, serving as combat engineers in the Canadian Forces. Although their physical fitness was not measured, their daily training schedule suggests that it was relatively high.

2.2 *Methods*

Physical fatigue was assessed in experiment A using a checklist (Harris *et al.* 1971) which asks the subject to rate himself against a list of ten descriptive phrases. Since the subjects in experiment B spoke only French and the descriptive phrases in the checklist translated badly, it was decided to prepare a new rating scale. In the new scale, subjects were asked to make a mark on a 100 mm line whose right and left ends correspond to *pas du tout* and *trop fatigue*. The difference between the rating scales is not sufficient to invalidate the conclusions drawn later regarding the fatigue state of the subjects.

Heart rates were recorded continuously by means of solid state data recorder (VITALOG Corporation, Palo Alto, California). Heart rates from the ten subjects were averaged every 10 s and stored in solid state memory. The stored data were transferred to disc and analysed using an Apple IIe computer. The data are presented in the following three formats:

(*a*) The average hourly HR was calculated for each hour of elapsed time (from the start of the sustained operation);

(*b*) Heart rates during specific tasks were analysed to show the percentage of time spent in each of three zones corresponding to light work (less than 120 beats min^{-1}), moderate work (120–140 beats min^{-1}) and heavy work (greater than 140 beats min^{-1}), as proposed by Christensen (1953);

(*c*) Specific tasks were analysed to show the time spent with a HR above (*w*) and below (*r*) 120 beats min^{-1}. The period *w* represents fatiguing work (Wells *et al.* 1957) and can be expected to decline with elapsed time in a sustained operation.

2.3. *Experimental scenario*

Experiments A and B were conducted during field manoeuvres carried out by Canadian combat engineers to test their capability for sustained operations. The scenarios for experiments A and B were based on the capability to create obstacles which will slow the enemy's advance and, in each, some or all of the following tasks were performed;

(*a*) In abatis, a road was blocked with trees from either side of the road, felled with chainsaws (1)†;

†Numbers in parentheses in figures correspond to the inserted numbers.

(*b*) a simulated minefield was prepared by burying dummy mines just below the surface (2);
(*c*) a road was blocked by forming large craters. The nine holes required for the explosive charges were prepared by one of two methods. In experiment A, the holes were made by driving hollow steel pipes (camouflet tubes) into the ground using a heavy (32 kg) hammer device raised and brought down forcibly on the top of the pipe by four men working in unison. In experiment B, the nine holes were dug by spade and auger (3);
(*d*) a barbed wire fence, 400–600 m in length, was constructed to deny a potential airstrip to the enemy (4);
(*e*) a temporary bridge was assembled from medium sized girders (5);
(*f*) an 8 km march was completed carrying 19 kg of equipment (6);
(*g*) trenches were dug with spades to create a defensive position (7).

The time between major tasks was spent moving from one worksite to another or preparing and eating meals. Although they were supervised by a Sergeant, the subjects were allowed to work at their own pace in both experiments. Observers recorded in detail the activities of each subject.

In experiment A, the four subjects were wakened at 0700 hours. Starting at 1600 hours, the sustained operation lasted 60 hours so that, except for 1–2 hours of sleep on the first night, the subjects were without sleep for 69 hours. The subjects carried out only one major task in the first 30 hours (*d* from preceeding list), but three tasks (*c* repeated three times) during the second half (see figure 1). In experiment B, the six subjects were wakened at 0515 hours, started at 0715 hours and continued working for 45 hours with brief rests but no opportunity for sleep; eleven major tasks (*a*–*g*) were completed (see figure 2).

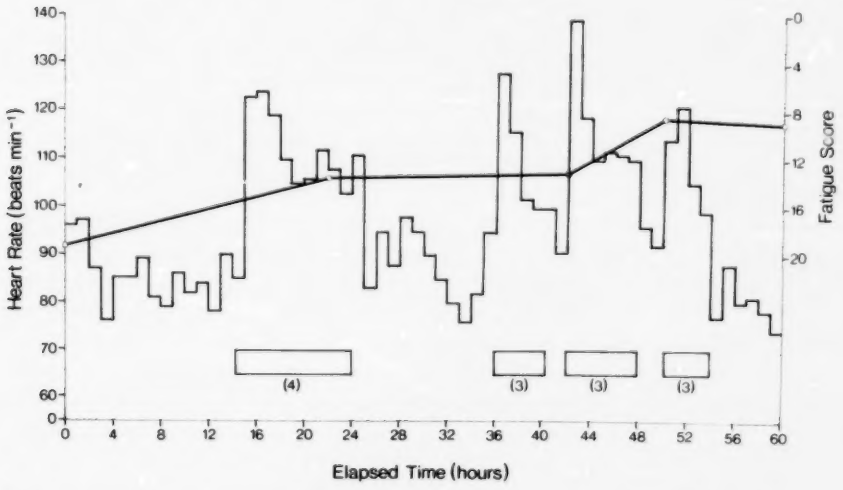

Figure 1. Hourly average heart rates and ratings of physical fatigue for experiment A. (Major tasks designated by the numbers in parentheses are described in Materials and Methods.)

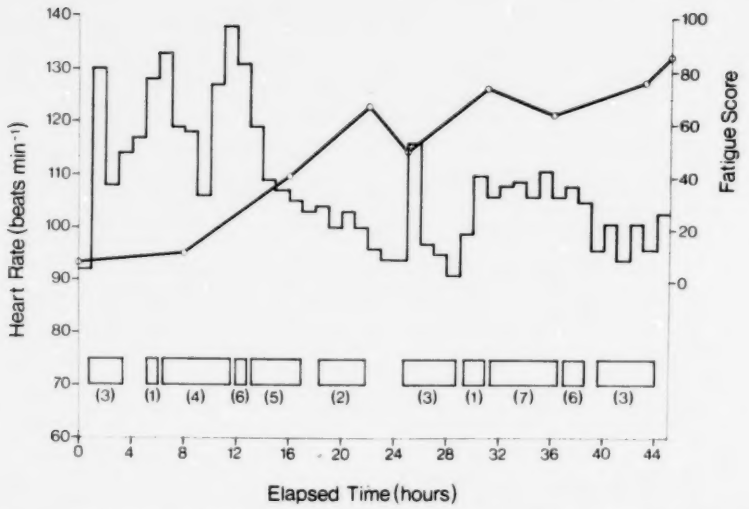

Figure 2. Hourly average heart rates and ratings of physical fatigue for experiment B. (Major tasks designated by the numbers in parentheses are described in Materials and Methods.)

3. Results

Figures 1 and 2 show the hourly average HRs and ratings of physical fatigue plotted against elapsed time. Although physical fatigue appeared to increase progressively with elapsed time in experiment A (figure 1), the initial value of 19.3 is unusually high (Myles 1985). Only the fourth and fifth values, before the third cratering task and at the end of the sustained operation, are in the range normally reported for fatigued subjects. In experiment B, ratings of physical fatigue increased rapidly in the first 24 hours to a relatively high level that was maintained throughout the second half without much further increase (figure 2).

Heart rates during selected tasks were analysed to indicate the intensity of exercise. For the three cratering tasks completed in the second half of experiment A, the analysis was restricted to the most physicaly demanding component, hammering the camouflet tubes into the ground (see Methods). For the first two tasks, HRs while hammering were below 120 beats min^{-1} for 8% and 18% of the time and above 140 beats min^{-1} for 55% and 46%, respectively (figure 3). In the third, the observer team reported that the subjects appeared fatigued compared to the first two tasks. This difference was reflected in the work intensity for the third cratering task; HRs for hammering were below 120 and above 140 beats min^{-1} for only 54% and 18% of the time, respectively (figure 3), significantly less than during the first two cratering tasks ($p < 0.05$).

For the three cratering tasks carried out in experiment B, HRs were analysed for the time spent digging the nine holes by auger and spade (see Methods). In this activity, HRs were below 120 beats min^{-1} for 20% of the time in the first, for 44% in the second and for 57% in the third (figure 4*a*). The percentage of time that the HR was above 140 beats min^{-1} decreased significantly ($p < 0.05$) from 44% in the first task to 16 and 12% during the second and third. The times taken to complete the nine holes were 25, 31 and 32 min, respectively.

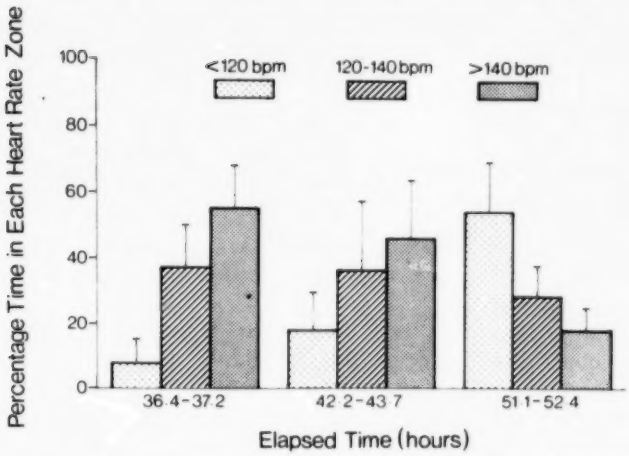

Figure 3. Work intensity based on heart rate for the three cratering tasks in experiment A.

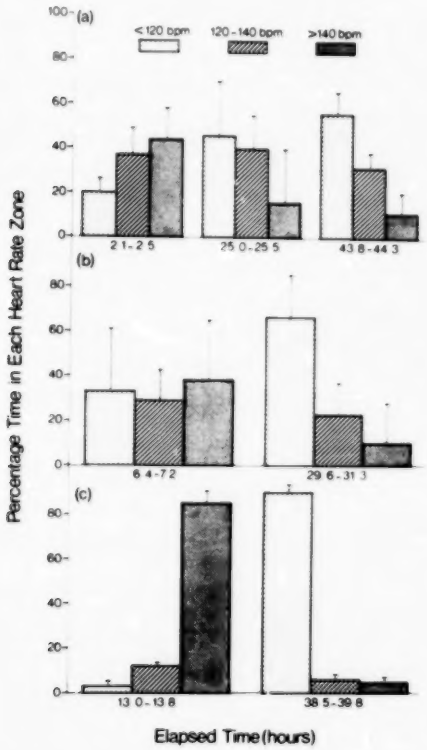

Figure 4. Work intensity based on heart rate for (*a*) cratering, (*b*) abatis and (*c*) the 8 km march in experiment B.

For the two abatis tasks (figure 4*b*) in experiment B, HRs were below 120 beats min^{-1} for 33% and 67% of the time and above 140 beats min for 38% and 10%; times for completion of the task were 46 and 81 min, respectively.

The subjects chose to alternate walking and running for the first 8 km march, but to walk during the second. This difference is reflected in the HRs (figure 4*c*) which were below 120 beats min^{-1} for 3% and 89% of the time and above 140 beats min^{-1} for 85% and 5%; times to complete the distance were 47 and 93 min, respectively.

Table 1 shows the average duration of w and r, the ratio w/r and the average HR for the period $(w + r)$ for hammering the nine camouflet tubes in each of the three cratering tasks carried out in experiment A. In the first and second cratering tasks, w/r was 11·4 and 7·6, respectively; in the third, w and r were approximately equal (1·04 vs. 1·18) and w/r was 0·9. Average HRs for $(w + r)$ were above 120 beats min^{-1} in the first two cratering tasks and below in the third.

Work and recovery data for digging the nine holes in the three cratering tasks and for the two abatis tasks carried out in experiment B are shown in table 2. As the sustained operation progressed, w declined and r increased significantly for both cratering and abatis. As a result, w/r was below 1·0 in the second 24 hours and the average HR for $(w + r)$ was less than 120 beats min^{-1}. Since marching tends to be a continuous activity, as compared to the intermittent work of cratering and abatis, w and r were not calculated for the two 8 km marches. The decline in work intensity is best expressed by the average HRs which were 163 ± 8 and 111 ± 5 beats min^{-1} for the first and second marches, respectively.

4. Discussion

It is well established that sleep deprivation has a detrimental effect on mood and mental performance and that this decrement is least in activities where the subject is interested and motivated (Angus and Heslegrave 1985, Johnson 1982, Wilkinson 1965). Boring mental tasks, where the subjects work at their own pace, can be expected to take longer to complete as the period without sleep increases. In contrast, since the physiological systems which determine the capacity for muscular exercise appear to be relatively unaffected by periods of sleep loss up to 65 hours (Corcoran 1964, Holland 1968, Pickett and Morris 1975, Webb *et al.* 1981), exercise which is paced externally, such as treadmill walking (Angus *et al.* 1985), is probably immune to sleep deprivation. In sustained combat engineer operations, the work performed is essentially self-paced and the effect of sleep deprivation is often compounded by

Table 1. Work (w) and recovery (r) data for cratering in experiment A.

Task	Elapsed time (hours)	w (min)	r (min)	w/r	Average heart rate (beats min^{-1})
Cratering					
1	36·2	$4·45 \pm 3·0$	$0·43 \pm 0·1$	11·4	147 ± 12
2	42·1	$3·49 \pm 3·1$	$0·54 \pm 0·4$	7·6	144 ± 14
3	50·4	$1·04 \pm 0·3$	$1·18 \pm 0·4$	0·9	123 ± 12

Note: Values are means ± SD for four subjects. Cratering refers to the time spent preparing nine holes using camouflet tubes. Statistical differences ($p < 0·05$) are indicated.

Table 2. Work (w) and recovery (r) data for cratering and abatis in experiment B.

Task	Elapsed time (hours)	w (min)	r (min)	w/r	Average heart rate (beats min $^{-1}$)
Cratering					
1	1·4	3·00 ± 1·4	0·78 ± 0·3	3·9	133 ± 8
2	24·6	2·53 ± 1·3	0·93 ± 0·2	2·7	122 ± 6
3	43·5	1·20 ± 0·4	1·57 ± 0·5	0·8	116 ± 7
Abatis					
1	5·3	3·90 ± 1·6	1·67 ± 0·7	2·3	133 ± 8
2	29·4	2·21 ± 1·4	3·93 ± 1·5	0·6	114 ± 6

Note: Values are means ± SD for six subjects. Cratering refers to the time spent digging nine holes with spade and auger. Significant differences ($p < 0·05$) are indicated.

physical fatigue. Self-paced work is therefore dependent on the interest and motivation of the subject and may well be sensitive to changes in mood induced by sleep loss and fatigue.

Experiment A provided an opportunity to assess the effect of sleep deprivation acting alone. In the first 30 hours, the subjects carried out only one major task and, except for two hours during this task, had hourly average HRs that were typical of sedentary activity (figure 1). Experiment B, with eleven major tasks, was intended to demonstrate the combined effect of sleep deprivation and physical fatigue. Hourly average HRs (figure 2) indicate that the energy expenditure was relatively high in the first 24 hours, but declined in the second half.

Sleep deprivation alone appeared to have no adverse effect on work intensity (figure 3) and the work pattern indicated by w and r (table 1) for the first two cratering tasks in experiment A. The evidence for this statement is that the data obtained were quite similar to those for the tasks performed in the first half of experiment B by subjects who were not yet sleep deprived. Although the subjects in experiment B were assigned a full schedule of tasks in the second half, work intensity declined (figure 4) and the w/r ratios (table 2) indicate that they worked for shorter periods.

If the decline in self-paced work intensity observed in the second half of experiment B was not due to sleep deprivation, then it may have been caused by physical fatigue superimposed upon sleep loss. In experiment A, the rating scales and the reports of the observer team agree that the subjects were not fatigued until just before the third cratering task. Work intensity and the w/r ratio declined for the third cratering task in experiment A compared to the first two, but were similar to the data for tasks performed in the second half of experiment B. In the latter experiment, physical fatigue was fully developed by the end of the first 24 hours (figure 2). The coincidence between the development of physical fatigue and the decline in self-paced work intensity suggests cause and effect.

Although the exact cause remains uncertain, it is clear that self-paced work output declined from initial levels in experiment B. The subjects worked relatively hard for the first 14 hours with an average HR (calculated from the data in figure 2) of 120 beats min^{-1}. As time progressed, work intensity declined and the average HR

for the last 31 hours was 102 beats min^{-1} (from figure 2). A HR of 120 beats min represents an energy expenditure of 35–40% of their VO_2max for fit young men such as the soldiers who served as subjects in this study (Wells *et al.* 1957). It is generally accepted that, in the absence of heat stress or dehydration, work such as cratering and abatis can be performed at a HR of 120 beats min^{-1} for eight hours without undue fatigue (Astrand and Rodahl 1977, Michael *et al.* 1961, Simonson 1971). Experiment B suggests that this level of energy expenditure can be maintained for longer than 8 hours, perhaps for 12–16 hours, before physical fatigue causes a reduction to a lower, but more sustainable level.

The results of the present study have important implications for sustained operations. Experiment B demonstrated that, although the goal of operating continuously for 48 hours was achieved, individual tasks took longer to complete in the later stages. For the three cratering tasks, time to complete the nine holes by auger and spade took progressively longer. A more dramatic decline was evident for the two abatis tasks and the two 8 km marches. This requirement for additional time must be taken into account when planning sustained operations. Another finding with important implications is that sleep deprivation, *per se*, did not effect self-paced work. This observation is consistent with reports that sleep loss has no effect on perceived exertion (Myles 1985) or walking speed on a 'self-paced' treadmill (Martin and Haney 1982, Soule and Goldman 1973). It means that soldiers who are sleep deprived, but not physically fatigued, can be expected to complete physically demanding tasks in the same time as fresh troops.

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L'effet de la privation de sommeil et de la fatigue physique sur le travail à rythme libre a été étudié au cours de deux expériences simulant des activités soutenues de génie de combat. Dans l'expérience A, quatre sujects ont été privés de sommeil pendant 69 heures. Durant cette période, ils n'effectuaient que quatre tâches physiquement astreignantes, dont trois au cours des dernières 24 heures. L'enregistrement en continu de la fréquence cardiaque (H.R) a montré que la privation sommeil, en l'absence de fatigue physique, n'avait pas d'effet sur l'intensité de travail et sur la durée du travail fatiguant (H. R au-dessus de 120 battements. mn $^{-1}$). Dans l'expérience B, six sujets ont réalisé le programme complet d'activités physiques intenses avec une privation de sommeil de 47 heures. Certaines des tâches à exécuter ont été répétées au moins une foix, de manière à pouvoir évaluer les effets de la privation de sommeil et de la fatigue physique. Durant les première 14 heures de l'expérience B, les sujets ont travaillé avec une H.R moyenne de 120 battements, mn $^{-1}$, ce qui correspond à une dépense énergétique équivalente à 35–40% de la consommation maximum d'oxygène pour des hommes jeunes en bonne forme physique. Au cours du temps restant, l'intensité due travail a baissé et les sujets ont travaillé à des H.R au-dessous de 120 battements. mn $^{-1}$ pendant des périodes plus courtes. Les questionnaires d'auto-évaluation ont confirmé que ces changements coïncidaient avec l'évolution de la fatigue physique. Puisque la privation de sommeil n'avait pas d'effet dans l'expérience A, on a conclu que la baisse d'intensité due travail auto-rythmé, dans l'expérience B, était attribuable à la combinaison de la fatigue physique et de la privation de sommeil.

Die Auswirkungen von Schlafentzug und physischer Ermüdung auf selbstbestimmte Arbeit wurden in zwei Experimenten untersucht, wobei Dauergefechtsoperationen simuliert wurden. In Experiment A verbrachten 4 Personen ohne Schlaf 69 Stunden. Während dieser Zeit führten sie nur 4 Aufgaben mit physischen Anforderungen aus, 3 von ihnen in den letzten 24 Stunden. Die kontinuierliche Ableitung der Herzschlagfrequenz (HR) zeigte, daß der Schlafentzug ohne physische Ermüdung keine Auswirkung auf die Arbeitsintensität und den Abschnitt mit

physischer Ermüdung bewirkte (HR über 120 Schläge pro Minute). In Experiment B führten 6 Personen einen ganzen Katalog von physisch belastenden Tätigkeiten bei einem Schlafentzug von 47 Stunden aus. Alle Tätigkeiten wurden mindestens so lange wiederholt, bis die Auswirkungen von Schlafentzug und physischer Ermüdung festgestellt werden konnten. Während der ersten 14 Stunden des Experiments B arbeiteten die Versuchspersonen bei einer mittleren Herzschlagfrequenz von 120 Schlägen pro Minute, was einem Energieverbrauch von 35–40% der maximalen O_2-Aufnahmekapazität bei einem gesunden jungen Mann entspricht. In der folgenden Periode sank die Arbeitsintensität und die Personen arbeiteten bei Herzschlagfrequenzen über 120 Schlägen pro Minute in kürzeren Zeitabständen. Subjektive Beurteilungen bestätigten, daß diese Veränderungen mit der Zunahme von physischer Ermüdung einhergingen. Wie der Schlafentzug in Experiment A ohne Auswirkungen blieb, zeigte die Abnahme der selbstvorgegebenen Arbeitsintensität in Experiment B einen Zusammenhang mit der physischen Ermüdung und dem Schlafentzug.

断眠と肉体疲労が自己ペース作業に及ぼす影響を持続戦闘工兵作業を模した2つの実験で決定した。実験Aでは4名の被験者が69時間睡眠をとらなかった。この期間被験者は4つの肉体的にきつい作業を実施した。その内の3つは最後の24時間に行った。心拍数（HR）の連続記録は肉体的疲労のない時，断眠が作業強度と疲労作業（120拍／秒のHR）の継続時間に影響を与えないことを示した。実験Bでは6名の被験者が47時間の断眠期間中に一連の肉体的にきつい作業を実施した。作業のいくつかは少なくとも一回繰り返して断眠と肉体疲労が評価できるようにした。実験Bの最初の14時間で被験者は健康な青年男子の最大酸素摂取量の35—40%のエネルギー消費量に相当する120拍／秒の平均HRで作業した。持続作業の残りでは，作業強度は低下し，被験者は120拍／秒以上のHRで短期間作業した。これらの変化が肉体疲労の発生と一致したことが評定尺度によって確認された。断眠は実験Aでは影響がなかったので，実験Bにおける自己ペース作業強度の低下は肉体疲労と断眠の結合によるものとされた。